EFFECTS OF POSTURAL STABILITY AND NEUROCOGNITIVE FUNCTION IN SPORTS CONCUSSION INJURIES

by

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EFFECTS OF POSTURAL STABILITY AND NEUROCOGNITIVE FUNCTION
IN SPORTS CONCUSSION INJURIES

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Objective: To determine the differences in postural stability measures and neurocognitive function between sport-related concussion, also known as mild head injury (MHI), subjects and healthy subjects. To determine the correlating factors of postural stability and neurocognitive function.

Design and Setting: This descriptive study design assessed postural stability and neurocognitive function within 7 days of athletes sustaining a sport-related MHI and compared the group to a control group of healthy subjects. All testing was completed at the University of Pittsburgh Neuromuscular Research Laboratory.

Subjects: Twenty subjects (10 healthy, 10 MHI) participated.

Measurements: All subjects completed a single testing session consisting of a computerized neurocognitive test and postural stability assessment, including kinematics and force plate data collection, during which two balance tasks were performed three times each.

Results: There were no significant differences in postural stability between groups. There were no significant differences in neurocognitive function. Additionally, no relationship existed between postural stability and neurocognitive function.

Conclusions: Although not significant, hip flexion and extension was larger in the control subjects, indicating that there may be difficulty for MHI subjects to adopt either a hip or ankle strategy to maintain postural stability. While no significance was found in the study, there may be trends to suggest that visual memory ($p=0.11$) and reaction time ($p=0.17$) are different. The low number of subjects and time of testing with relation to injury may be contributing factors in the lack of significant results in the majority of test variables.

Key Words: sports concussion, mild head injury, postural stability, force platform, kinematics, neurocognitive function

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PREFACE

I would first like to thank Dr. Joseph Myers for his guidance and encouragement over the course of my graduate studies. His support, teachings, and extensive history in sports medicine research have contributed tremendously to my personal development as both an individual and professional.

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1. INTRODUCTION

The increased number of recent research studies suggests that concussion in sports, also referred to as mild head injury (MHI), has only recently become a topic of concern. Yet, despite the fact that the number of concussions today exceeds those observed sixty years ago, sports concussions have occurred since athletics began centuries ago (Maroon, Lovell et al. 2000; Guskiewicz, Ross et al. 2001; Powell 2001). Each year, it is estimated that approximately 300,000 brain injuries occur, resulting in as many as 900 deaths (Grindel, Lovell et al. 2001). Although a majority of concussions are mild, some of them are severe and may result in long-term medical concerns (Collins, Lovell et al. 2002; Lovell, Collins et al. 2003; Guskiewicz, Bruce et al. 2004). As the size, speed, and skill of the competitive athlete increases, concussions will continue to be an increasing cause for concern (Naunheim, McGurren et al. 2002). The popularity of sports and sport participation may also be a contributor to the rise in concussion prevalence. Concurrently, the number of definitions, scales, and return to play guidelines has increased tremendously leading to improper management and even unnoticed injury (Guskiewicz, Riemann et al. 1997; Collins, Lovell et al. 1999; Maroon, Lovell et al. 2000; Oliaro, Anderson et al. 2001; Collins, Iverson et al. 2003; Peterson, Ferrara et al. 2003; Piland, Motl et al. 2003). In a recent study of football and soccer athletes, only 23.4% of the football players and 19.8% of the soccer players realized that the symptoms they had suffered represented a concussion (Delaney, Lacroix et al. 2002). Despite recent concern and research in MHI in sports, the mechanism of injury, management, and recovery time remains unclear.

Components of concussion assessment include, but are not limited to, symptom reporting, neurocognitive function, and postural stability (Collins, Lovell et al. 1999; Lovell, Iverson et al.

1999; Wojtys, Hovda et al. 1999; Guskiewicz 2001; Guskiewicz, Ross et al. 2001; Collins, Iverson et al. 2003; McCrea, Guskiewicz et al. 2003). Neurocognitive function is controlled by the central nervous system and can be measured through processing speed, verbal memory, visual memory, reaction time, and attention span (Collins, Iverson et al. 2003). Many researchers agree that testing neurocognitive function has become a valuable tool in the management of cerebral concussion (Macciocchi, Barth et al. 1996; Wojtys, Hovda et al. 1999; Kelly 2000; Grindel, Lovell et al. 2001; McCrea 2001; Hinton-Bayre and Geffen 2002; Collie and Maruff 2003). Research in this area has shown that deficits in neurocognitive function have been evident up to 8 days post-injury (Collins, Iverson et al. 2003). Computerized testing, such as the Immediate Postconcussion Assessment and Cognitive Test (ImPACT), is becoming more of a standard in evaluating and managing MHI in sports as it both highly sensitive and accurate in assessing the injury (Lovell, Collins et al. 2001).

Another potential concussion assessment tool is postural control testing. Postural control is the ability to maintain balance in any given environment (Stoffregen, Smart et al. 1999; Guskiewicz 2001). Recently it has been demonstrated that concussion affects the areas of the brain that are responsible for the maintenance of postural equilibrium (Riemann and Guskiewicz 2000; Guskiewicz, Ross et al. 2001; Peterson, Ferrara et al. 2003). Athletes may have sensory interaction problems during the acute phase of MHI recovery, indicating that the symptoms responsible for postural control are affected (Guskiewicz, Riemann et al. 1997; Guskiewicz 2001). Postural stability studies in the past have also shown that subjects with MHI demonstrate significant levels of postural instability when compared to healthy subjects (Riemann and Guskiewicz 2000; Guskiewicz, Ross et al. 2001). In addition, the latest research in area of postural stability has relied mostly on measurements with very expensive equipment

(Guskiewicz, Perrin et al. 1996; Riemann and Guskiewicz 2000; Guskiewicz 2003). To our knowledge, no concussion study has used the force platform alone to measure this component, although it has been used to evaluate postural stability of the healthy population in the past (Goldie, Bach et al. 1989).

Although postural stability assessment and neurocognitive function are critical in the assessment of MHI, each alone may not fully explain the complex nature of symptoms and etiology. Despite advances in understanding postural stability and neurocognitive function following MHI in sports, little research has been carried out to correlate the results to each other. Therefore, the purpose of this study was to determine the difference between sport-related MHI subjects and healthy control subjects in both postural stability and neurocognitive function and to assess the correlating factors of these components. We believe that these findings may provide the sports medicine professional with more objective information when managing sport-related concussion and understanding the components necessary to provide a full recovery and return to sport.

2. METHODS

2.1. Subjects

Twenty subjects were recruited from high schools, colleges, and universities in the Western Pennsylvania area. The subject demographics (all subjects, MHI subjects, and healthy subjects) are listed in **Table 1**. **Table 2**, **Table 3**, **Table 4**, **Table 5**, **Table 6**, **Table 7**, **Table 8**, **Table 9**, **Table 10**, and **Table 11** represent the characteristics of the concussive case of each MHI subject. All subjects signed an informed consent prior to participation in this study based on requirement by the University of Pittsburgh Institutional Review Board. Individuals with a history of lower extremity injury history or current presence of any neurological function disorder that had potential of affecting the performance of postural stability testing were excluded from the study. Subjects in the MHI group were free of any lower extremity pathology in the previous six months and were diagnosed with his or her first sport-related concussion. Diagnoses were determined by the two neuropsychologists of the Sports Concussion Program at the Center for Sports Medicine of the University of Pittsburgh Medical Center (UPMC; Pittsburgh, PA, U.S.A.). Subjects in the MHI group were tested within 7 days of the injury. The healthy subjects had no previous history of concussion, no lower extremity pathology in the previous six months, and were matched to the MHI subjects according to gender, age, height, weight, and sport.

2.2. Instrumentation

Neurocognitive function and symptom reporting were evaluated within 7 days of the injury using ImPACT software version 3.0 (NeuroHealth Systems, LLC; Pittsburgh, PA, U.S.A.). Postural stability measurements were assessed using a three-dimensional kinematic motion analysis system and a force platform. Three-dimensional kinematic data (joint angles, joint velocities, and joint accelerations) were collected by the Peak Motus 3D Motion Analysis System (Peak Performance Technologies, Inc.; Englewood, CO, U.S.A.), which consists of six high-speed optical cameras (Pulnix Industrial Product Division; Sunnyvale, CA, U.S.A.) operating at a frequency of 120 Hz. A set of 29 retroreflective markers were placed on each subject to collect the data during the balance tasks (**Figure 1**). Only 15 markers (lower extremity and pelvis) were used for analysis in this study. Prior to testing, camera calibration was conducted according to the manufacturer's guidelines with an acceptable wand calibration of less than 0.0025 m mean residual error. Force plate measures were obtained from a Kistler piezoelectric force platform (Kistler Instrument Corp.; Amherst, NY, U.S.A.). The force platform was used to collect ground reaction forces in the anterior-posterior, medial-lateral, and vertical directions and calculate the center of pressure. Raw voltage data from the force plate were collected through an analog to digital (A/D) converter board (DT3010/32; Data Translation, Inc.; Marlboro, MA, U.S.A.) to the connecting desktop computer with the Peak Motus software system (version 7.2, Peak Performance Technologies, Inc., Englewood, CO, U.S.A.). A sampling frequency of 1200 Hz was used to collect the force platform data.

2.3. Procedures

ImPACT testing was administered in an isolated room to eliminate any distraction that could potentially alter the outcome of the test. Composite scores were recorded for verbal memory, reaction time, verbal motor processing speed, visual memory, and total symptom score. Anthropometric data were collected for all subjects prior to kinematic and force platform data collection as described by Chandler et al. (Chandler, Clauser et al. 1975) Body mass and height were measured on a standard height and weight scale (Health O Meter, Inc.; Bridgeview, IL, U.S.A.). An anthropometer (Lafayette Instrument Co., Lafayette, IN, U.S.A.) and tape measure

(Gulick II Measuring Tape: Country Technology, Inc., Gays Mills, WI, U.S.A.) were used for measurement of the body segments of each subject. Retroreflective markers (Peak Performance Technologies, Inc., Englewood, CO, U.S.A.) were positioned on each subject for collection of lower extremity and pelvic kinematic data collection during the postural stability testing. The marker system used was based on Kadaba et al (Kadaba, Ramakrishnan et al. 1990) as developed at the Helen Hayes Hospital in New York.

Postural stability testing consisted of two tasks: single-leg with eyes open (SEO) and single-leg with eyes closed (SEC). In the SEO trial, the subject stood directly on the force plate on his or her dominant leg with the eyes open (**Figure 2**). In the SEC trial, the subject stood directly on the force plate on his or her non-dominant leg with the eyes closed (**Figure 3**). The non-dominant leg is defined as the leg the subject would use to kick a ball. Balance tasks were measured directly on the Kistler force platform. Three trials of each balance task were performed randomly, with each trial lasting 20 seconds. A 30 second rest period was given between each trial. The subject was given details of the trial length, stance, and position prior to data collection. All trials were performed with hands on the iliac crests. During the balance tasks, the untested limb was slightly flexed at both the hip and knee, with the non-supporting foot no more than 10 cm off the standing surface. Touchdowns on the force plate were accepted. In any trial where the subject touched his or her foot off the force plate, the trial was stopped and repeated.

Before the first trial began, the subject was instructed to remain as still as possible, maintain the test position, return to that position as quickly as possible in the case where balance was lost, and to make sure that his or her legs did not make contact with each other. A visual target was placed on the wall about 2.5 m in front of the force platform to aid in maintaining neutral head position. The subject was asked to focus on the target for SEO trials and to use the target to find the initial balance position prior to closing eyes in the SEC trials. Testing and data collection was initiated as soon as the full testing position was reached.

2.4. Data Reduction

ImPACT total symptom scores and composite scores were recorded from the calculated values of the software program and exported into a database for analysis. A set of 22 concussion symptoms were given in the software for the athlete to rate the severity of each on a scale of 0 (not experiencing) to 6 (severe); the total score was determined by adding the scores of each symptom. In addition to total symptom score, the composite scores exported included verbal memory, visual memory, visual motor speed, and reaction time. Three-dimensional coordinate data from all balance tasks were filtered with a 4^{th}-order Butterworth filter using a method developed by Jackson (Jackson 1979) to determine optimal cut-off frequency. Maximum and minimum values as well as the standard deviations of the hip, knee, and ankle joint angles were calculated for sagittal and frontal plane movements. Dependent variables included standard deviations of the following: hip flexion/extension, hip abduction/adduction, knee flexion/extension, knee valgus/varus, ankle plantarflexion/dorsiflexion, and ankle inversion/eversion. Joint angles were calculated using calculations within the KineCalc module of the Peak Motus software (Peak Performance Technologies, Inc., Englewood, CO, U.S.A.). These calculations were based on the methods of a previously published work (Vaughan, Davis et al. 1999). Data were averaged for three trials for each test condition.

Using the Kistler force platform system and Peak Motus software, the following variables were collected: anterior-posterior (AP), medial-lateral (ML), and vertical (V) ground reaction forces (GRF); and the x- and y-coordinates of the center of pressure. Standard deviations of the ground reaction forces were calculated within the KineCalc module of the Peak Motus software and are reported in this study as AP GRF, ML GRF, and V GRF, all which were measured in Newtons. The variability of the center of pressure coordinates from the force platform was further analyzed to calculate total postural sway in meters. All variables were analyzed through a custom program in Matlab Version 6.0 Release 12 (The Mathworks, Inc.; Natick, MA, U.S.A).

2.5. Statistical Analysis

Statistical analysis included pairwise dependent t-tests between groups (MHI versus control) for each of the postural stability variables (force platform and kinematic) and for each of the neurocognitive variables for each balance condition (SEO versus SEC). In order to determine if correlations existed between postural stability measures and neurocognitive function, Pearson product-moment correlation coefficients were calculated between each neurocognitive variable and the postural stability variables for each balance condition. All statistical analyses were computed with an alpha level of 0.05 set a priori. All statistical calculations were completed using Stata statistical software (Stata 8.0; Stata Corporation, College Station, Texas).

3. RESULTS

Table 1 lists the comparisons between age, height, and body mass, ensuring subject matching. No significant differences existed between the MHI and control groups. Time since injury was recorded at testing for all MHI subjects. The mean time since injury was 58.1 ± 45.8 hours, indicating that the average time was between 2 and 3 days. **Table 2**, **Table 3**, **Table 4**, **Table 5**, **Table 6**, **Table 7**, **Table 8**, **Table 9**, **Table 10**, and **Table 11** represent the individual concussion cases for the MHI subjects 1 through 10, respectively. There were no significant group differences in the force platform or kinematic data. All biomechanical results are presented by condition in **Table 12** (SEO task) and **Table 13** (SEC task). There were no significant group differences in the neurocognitive function data. Group comparisons for all neurocognitive test scores are presented in **Table 14**. No significant correlations within all subjects combined (both MHI and control groups) in either condition (SEO and SEC) were found. Correlations between neurocognitive and posture variables for SEO and SEC are presented in **Table 15** and **Table 16,** respectively.

4. DISCUSSION

Assessing postural stability and neurocognitive function following a sport-related concussion are becoming more common in the sports medicine setting. However, understanding the combined effects of these assessment tools remains unclear. The purpose of this study was to determine the differences between MHI and healthy subjects in postural stability and neurocognitive function, as well as determine the relationship between the two assessments.

4.1. Postural Stability

The current study evaluated postural instabilities with the use of a force platform and motion analysis system. The results of the current study suggest that concussed athletes have no difference in postural stability measures compared to healthy athletes. Although no significant results were found, some of the data are noteworthy. As shown in **Table 12**, the mean hip flexion and extension movement in the SEO condition was 0.9 for the MHI group and 1.8 for the matched controls. In **Table 13**, the mean for this variable in the SEO condition was 1.7 for the MHI group and 3.0 for the matched controls. The ankle movements between groups tended to be similar in values. Although none of the results were significant, trends may or may not exist. These numbers may indicate that healthy athletes adopt a hip strategy for postural stability in single leg balance tasks while athletes sustaining MHI tend not to adopt any strategy for postural stability following injury, which may or may not be associated with some type of deficit of the body's postural control system.

Researchers who study postural stability in concussed athletes vary in terms of what is considered the adequate recovery time of deficits in this area; however, most MHI researchers agree that postural instabilities are apparent following a concussive event (Guskiewicz, Riemann et al. 1997; Basford, Chou et al. 2003; McCrea, Guskiewicz et al. 2003; Peterson, Ferrara et al. 2003). While Guskiewicz et al (Guskiewicz, Riemann et al. 1997) and McCrea et al (McCrea, Guskiewicz et al. 2003) have demonstrated postural instabilities up to 5 days post-injury in collegiate athletes, Peterson et al (Peterson, Ferrara et al. 2003) found composite balance measures to be significantly different compared to a healthy group through 10 days post-injury. Peterson et al (Peterson, Ferrara et al. 2003) demonstrated a longer time for recovery, but also determined that the athletes' reported balance symptoms (dizziness, loss of balance, etc) were significant only through day 3 post-injury. This means that although an athlete may feel that they have balance difficulties only for a few days following a concussion, deficits are most likely apparent for about a week following this sense of absence. Although statistical analyses were not performed between the conditions, other studies have evaluated eyes open and eyes closed balance situations. Taking vision out of the picture will result in larger movements of the limbs in order to maintain postural stability (Guskiewicz, Riemann et al. 1997; Guskiewicz 2001), whether concussed or not.

Recent studies have demonstrated postural instabilities following concussion with the use of sophisticated, expensive measuring systems (Guskiewicz, Perrin et al. 1996; Riemann and Guskiewicz 2000; Guskiewicz 2003). This was the first study to evaluate postural stability through force platform measurements and kinematics in concussed athletes. Few studies have evaluated single leg balance tasks in concussed and healthy subjects with use of the sophisticated balance systems (Riemann and Guskiewicz 2000; Guskiewicz 2001). Although significance was found in those studies, it is unclear whether or not it is a sensitive measure outside of the balance system used in these studies. We expected differences to exist in ground reaction forces, joint angles, and postural sway; however, the force platform and kinematic measures may not be sensitive enough to assess differences between MHI and control groups with single-leg balance tasks. The aforementioned studies also evaluated the athletes within 3 days of injury. In the current study, there was a considerable difference among the MHI subjects for the time between injury and time of testing, in spite of the low mean. This also may be why differences were not seen in these individuals. It is also worth mentioning that the biomechanics of each injured athlete may have played a role in the outcomes found in the study. The areas of the brain that are responsible for the maintenance of postural equilibrium have been demonstrated to be affected in concussion (Riemann and Guskiewicz 2000; Guskiewicz, Ross et al. 2001; Peterson, Ferrara et al. 2003). More specifically, the cerebellum sits in the back of the head and is mainly responsible for maintaining balance (Van De Graaff and Fox 1999). No significant values were found between subjects in the balance tasks, but that may be related to the number of subjects who had trauma to this area of the brain.

4.2. Neurocognitive Function

The results of the current study suggest that there are no significant differences between concussed and healthy athletes in terms of neurocognitive function. However, there may be trends toward differences in visual memory (p=0.11) and reaction time (p=0.17). As shown in **Table 14**, the mean visual memory composite score (out of 100 possible points) for the MHI group was 73.98 ± 10.71 and 80.57 ± 6.34 for the control group; the mean reaction time was 0.60 seconds ± 0.09 for the MHI group and 0.54 seconds ± 0.08 for the control group.

Previous research has demonstrated that neurocognitive deficits are evident up to 8 days post-concussion (Collins, Iverson et al. 2003). Collins et al (Collins, Lovell et al. 2002) have demonstrated in a study involving high school athletes that highly significant differences in memory performance exist following any grade of concussion. Because each concussion should be treated individually, the time between testing and when the athlete is injured may be an issue in the current study. Although the mean time was relatively low, the standard deviation was high indicating that there was quite a difference in the time since injury among the subjects. All subjects were tested within 7 days of the injury, however it may be that with the low number of subjects there were also not as many higher degrees of severity of the concussions. Recent studies utilizing ImPACT data have involved hundreds of subjects (Lovell and Collins 1998; Collins, Grindel et al. 1999; Collins, Lovell et al. 2002; Collins, Field et al. 2003; Collins, Iverson et al. 2003; Lovell, Collins et al. 2003). The current study evaluated 20 total subjects, with 10 in each group. There may not have been enough data to find significance, as it has been demonstrated in many of the previous studies mentioned.

Sensitivity of neurocognitive testing is not an issue in the current study. Specifically for ImPACT, it is a sensitive assessment tool (Lovell, Collins et al. 2001) and other studies describe that neurocognitive testing, in general, currently is the most sensitive objective method for detecting deficits (Macciocchi, Barth et al. 1996; Wojtys, Hovda et al. 1999; Erlanger, Saliba et al. 2001). As with the postural stability findings, it may be that differences were not found in the current study because of biomechanical issues in each subject’s concussive injury. Few studies have done research in the area of biomechanics of injury (Van De Graaff and Fox 1999; Bailes and Hudson 2001; Barth, Freeman et al. 2001). Where the athlete is hit or the location of trauma in the brain may play a role in the manifestations of the individual concussion. An athlete who is struck in the back of the head may endure more deficits in the area of reaction time, while trauma in the left frontal part of the head may result in deficits in verbal memory and in visual memory when trauma is present in the right frontal part of the head. In the current study, each MHI subject presented with varying locations of impact compared with the others in the group.

4.3. Relationships Between Postural Stability and Neurocognitive Function

Despite advances in understanding postural stability and neurocognitive function following MHI in sports, little research has been carried out to correlate the results to each other. The current study demonstrated that no relationship existed between postural stability and neurocognitive function. We expected to find correlations between some of the postural stability and neurocognitive variables, particularly when considering the neuroanatomy. For instance, the cerebellum functions to aid in balance and coordination, whereas the reticular activating system controls and reaction time and alertness. Because both structures are located in the back of the head, our thought was that reaction time may have correlated with one or more of the postural stability variables.

One study has examined correlations between postural stability and neurocognitive function, but used the sophisticated balance system and neurocognitive tests other than ImPACT (Ross, Guskiewicz et al. 2000). In addition to finding no significant relationships between the measures, the authors also found no combination of variables that best predicted symptom severity at 1 and 2 days post-concussion. Relationships may not have been found because of the lack of significance between groups for the postural stability and neurocognitive function measures. Whether or not a force platform and kinematic assessment is sensitive enough to detect differences in MHI and control subjects has yet to be determined.

Understanding relationships between postural stability measures and neurocognitive function is important as returning an athlete to participation in sport becomes an issue. Whether or not relationships truly exist, both assessment tools have been proven individually to be sensitive to detecting deficits due to sport-related MHI. It is known that several grading scales and return to play parameters are available to aid in managing MHI. However, all vary significantly from one another on a consensus of when to return an athlete safely (Lovell, Iverson et al. 1999; Wojtys, Hovda et al. 1999; Bailes and Hudson 2001; Collins, Field et al. 2003). Concussion grading scales lack empirical evidence and can mislead the sports medicine professional to return an athlete too quickly (Collins, Lovell et al. 1999). In addition, a few of the more widely used scales lack any mention of postural instability issues following a concussive insult to the athlete. Because of the ambiguity and lack of education to coaches, athletes, and other personnel, reporting rates are low and unrecognized injuries have become a vital issue (Delaney, Lacroix et al. 2002). Therefore, even a small blow to the head should warrant proper evaluation including both a postural stability and neurocognitive assessment. Continued refinement and moderations of current grading scales are crucial as findings demonstrate more clarity to this complex injury.

4.4. Limitations

In assessing the results of this study, there are limitations that should be recognized. Based on previous MHI studies and the current study, the subject number was too low to detect any significant differences between groups for neurocognitive function and postural stability results or within groups for correlative results. Performing a sample size estimate for just the visual memory score variable indicated that 28 subjects were needed in each of the two groups to yield 80% power. A second limitation is that the current study only utilized the ImPACT software as a means to measure neurocognitive deficits in athletes. There are several tools available to evaluate neurocognitive function following a concussive event. Although it has been demonstrated as a useful option for the sports medicine clinician, we realize that the software may not be accessible to everyone. It is worth mentioning, however, that several other tools exist to measure the same components of verbal and visual memory, reaction time, processing speed, and symptoms. It is unclear whether or not other neurocognitive testing tools are more or less sensitive than ImPACT; further testing should be completed in the future to assess this. Nevertheless, using any form of neurocognitive test can and should be used to assess deficits in this area. Because each concussion is different, the location of hit and time since hit may have also been a factor in this study. The time between injury and testing, although relatively low in terms of the mean, had a large amount of variability among the MHI subjects. Another limitation is that assessing postural stability and neurocognitive function are two large components, but other factors do exist and may play a role. The current study solely assessed athletes with his or her first mild head injury and did not separate factors from one another, such as amnesia and loss of consciousness. Future research is warranted in sport-related MHI to address these issues and to potentially find significant results that were not found as a result of the limitations in the current study.

4.5. Conclusion

Although the results of this study did not show significance between groups in any of the variables, it is unclear whether or not a trend exists toward differences in visual memory and reaction or that MHI subjects struggle to adopt a hip or ankle strategy to maintain postural stability following injury. It is for certain that removing visual input from a balance task increases the difficulty to maintain postural stability, whether concussed or not. However, despite the results of the current study, both postural stability and neurocognitive function have individually been proven significant and sensitive to determine the deficits for those with MHI. Thus, using only one measure of concussion assessment should be avoided. When treating sport-related concussion, the sports medicine professional should evaluate and follow-up by assessing both postural stability and neurocognitive function along with symptom reporting. By adopting these factors into a global evaluation method of managing athletes with MHI, the course of recovery of each individual concussion may be better understood.

APPENDIX A

Tables and Figures

Table 1. Subject Demographics by Group

	All Subjects	MHI Subjects	Healthy Subjects	p-value
Age (years)	17.4 ± 2.0	17.3 ± 2.1	17.4 ± 2.0	0.73
Height (m)	1.7 ± 0.1	1.63 ± 0.1	1.7 ± 0.1	0.18
Body Mass (kg)	69.9 ± 8.5	68.7 ± 8.2	71.0 ± 9.1	0.46

Means and standard deviations for each group and p-value for between groups; ♋.05

Table 2. MHI Subject 1			
Subject Characteristics		**Concussion Characteristics**	
Age:	16 years	**Mechanism/Location of Impact:**	back of head on wrestling mat
Gender:	Male	**Concussion Details:**	disorientation
Sport:	Wrestling	**Symptoms:**	headache
Time:	60 hours		
		Symptom Score:	2

Time= time between injury and testing

Table 3. MHI Subject 2			
Subject Characteristics		**Concussion Characteristics**	
Age:	17 years	**Mechanism/Location of Impact:**	back of head on softball field
Gender:	Female	**Concussion Details:**	loss of consciousness, anterograde amnesia, disorientation
Sport:	Softball	**Symptoms:**	headache, dizziness or balance problems, visual changes, personality change, fatigue
Time:	24 hours		
		Symptom Score:	56

Time= time between injury and testing

Table 4. MHI Subject 3			
Subject Characteristics		**Concussion Characteristics**	
Age:	16 years	**Mechanism/Location of Impact:**	no data
Gender:	Female	**Concussion Details:**	loss of consciousness, anterograde amnesia, disorientation
Sport:	Rugby	**Symptoms:**	headache, dizziness or balance problems, nausea, numbness or tingling, fatigue
Time:	12 hours		
		Symptom Score:	18

Time= time between injury and testing

Table 5. MHI Subject 4			
Subject Characteristics		**Concussion Characteristics**	
Age:	18 years	**Mechanism/Location of Impact:**	head hit opponent knee and then ground
Gender:	Female	**Concussion Details:**	loss of consciousness, anterograde amnesia, disorientation
Sport:	Rugby	**Symptoms:**	headache, dizziness or balance problems, fatigue
Time:	36 hours		
		Symptom Score:	19

Time= time between injury and testing

Table 6. MHI Subject 5			
Subject Characteristics		**Concussion Characteristics**	
Age:	18 years	**Mechanism/Location of Impact:**	no data
Gender:	Female	**Concussion Details:**	no data
Sport:	Rugby	**Symptoms:**	no data
Time:	24 hours		
		Symptom Score:	8

Time= time between injury and testing

Table 7. MHI Subject 6			
Subject Characteristics		**Concussion Characteristics**	
Age:	18 years	**Mechanism/Location of Impact:**	head kicked several times in game
Gender:	Female	**Concussion Details:**	disorientation
Sport:	Rugby	**Symptoms:**	headache, dizziness or balance problems, nausea, fatigue
Time:	36 hours		
		Symptom Score:	60

Time= time between injury and testing

Table 8. MHI Subject 7			
Subject Characteristics		**Concussion Characteristics**	
Age:	15 years	**Mechanism/Location of Impact:**	head hit with field hockey stick
Gender:	Female	**Concussion Details:**	disorientation
Sport:	Field Hockey	**Symptoms:**	headache, dizziness or balance problems, nausea, fatigue, sensitivity to light and noise
Time:	26 hours		
		Symptom Score:	59

Time= time between injury and testing

Table 9. MHI Subject 8			
Subject Characteristics		**Concussion Characteristics**	
Age:	18 years	**Mechanism/Location of Impact:**	front of head hit ice
Gender:	Male	**Concussion Details:**	anterograde amnesia
Sport:	Ice Hockey	**Symptoms:**	headache, dizziness or balance problems, fatigue, feeling mentally foggy
Time:	114 hours		
		Symptom Score:	17

Time= time between injury and testing

Table 10. MHI Subject 9			
Subject Characteristics		**Concussion Characteristics**	
Age:	20 years	**Mechanism/Location of Impact:**	front of head hit diving board
Gender:	Female	**Concussion Details:**	retrograde and anterograde amnesia, disorientation
Sport:	Diving	**Symptoms:**	headache, dizziness or balance problems, nausea, fatigue, drowsiness, sensitivity to light
Time:	140 hours		
		Symptom Score:	38

Time= time between injury and testing

Table 11. MHI Subject 10			
Subject Characteristics		**Concussion Characteristics**	
Age:	21 years	**Mechanism/Location of Impact:**	elbowed in head by opponent; head hit ground
Gender:	Female	**Concussion Details:**	anterograde amnesia and disorientation
Sport:	Basketball	**Symptoms:**	headache, dizziness or balance problems, nausea, fatigue, sensitivity to light and noise
Time:	109 hours		
		Symptom Score:	25

Time= time between injury and testing

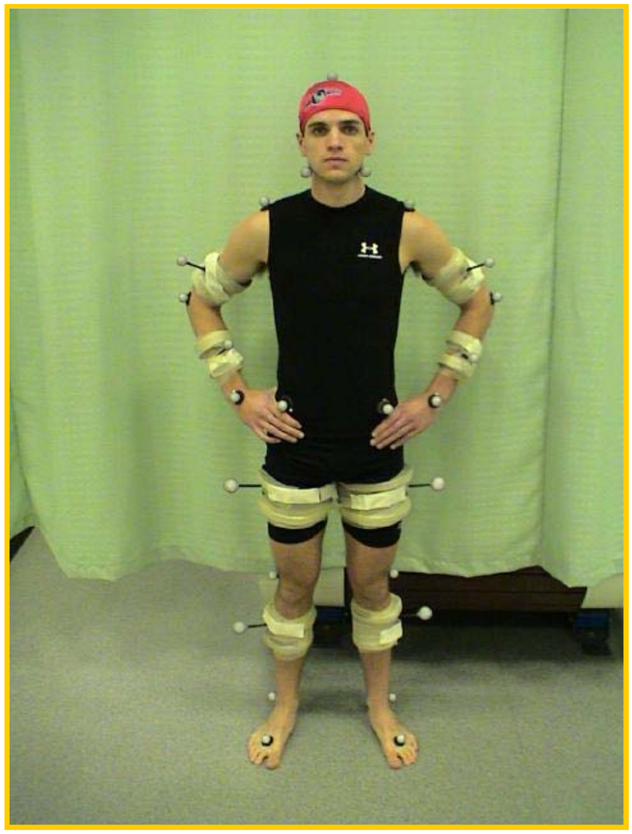

Figure 1. Retroreflective Marker Placement

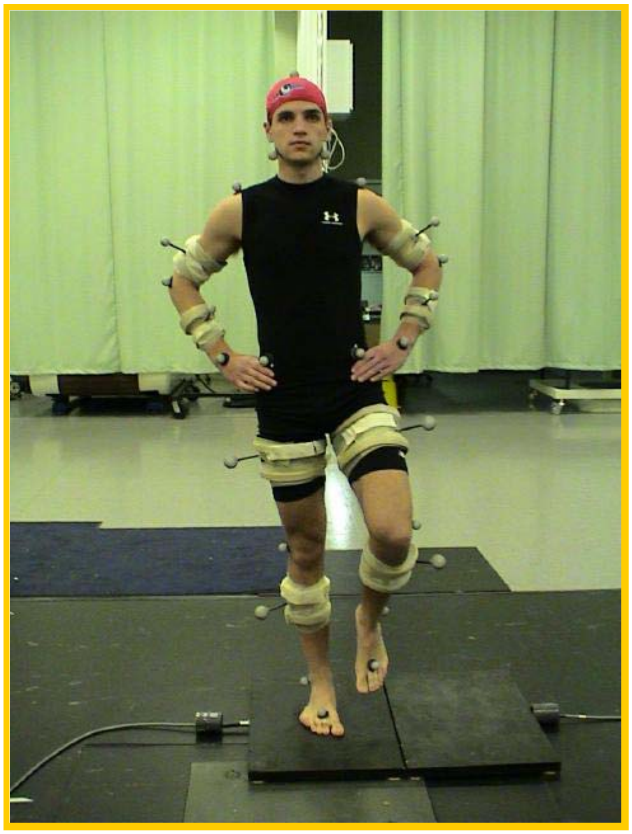

Figure 2. Single leg Eyes Open

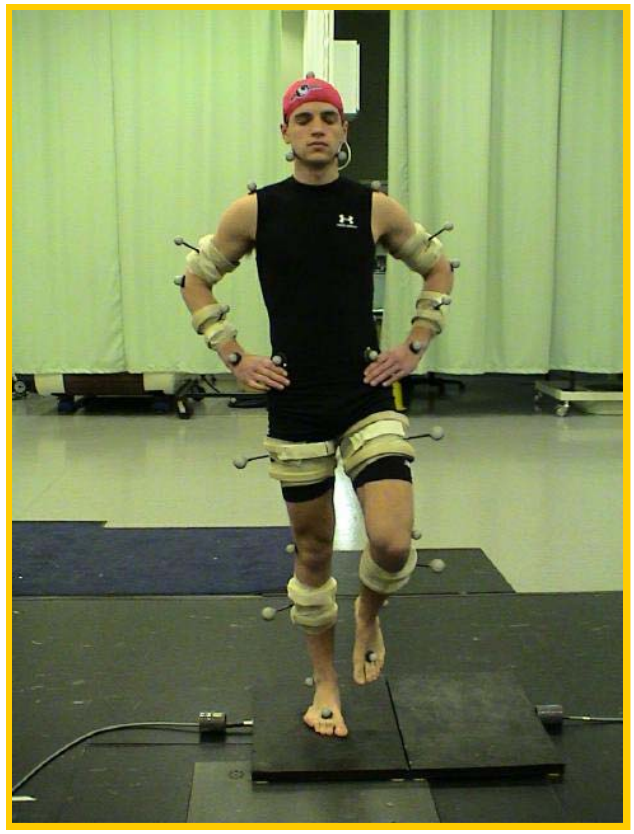

Figure 3. Single leg Eyes Closed

Table 12. SEO Postural Stability

Variables	MHI		Control		p-value
	Mean	SD	Mean	SD	
AP GRF	2.7	0.66	3.0	1.29	0.44
ML GRF	3.4	1.01	3.4	1.42	0.99
V GRF	5.3	2.79	5.1	2.46	0.86
Total Sway	0.9	0.23	0.8	0.20	0.73
Hip F/E	0.9	0.27	1.8	2.88	0.37
Hip Add/Abd	0.9	0.29	1.6	2.19	0.34
Knee F/E	1.1	0.43	1.8	2.81	0.41
Knee Val/Var	0.5	0.15	1.0	1.50	0.36
Ankle PF/DF	0.8	0.32	1.1	1.31	0.51
Ankle I/E	1.8	0.57	2.2	1.79	0.46

GRF = Ground Reaction Force, AP = Anterior/Posterior, ML = Medial/Lateral,

V = Vertical, F/E = Flexion/Extension, Add/Abd = Adduction/Abduction,

Val/Var = Valgus/Varus, PF/DF = Plantarflexion/Dorsiflexion, I/E = Inversion/Eversion

p-value based on pairwise two-sample t-test; ♋.05

Table 13. SEC Postural Stability

Variables	MHI		Control		p-value
	Mean	SD	Mean	SD	
AP GRF	4.7	1.44	5.2	1.81	0.43
ML GRF	6.6	2.11	8.1	3.64	0.26
V GRF	9.9	4.32	10.1	4.50	0.92
Total Sway	1.5	0.31	1.5	0.39	0.76
Hip F/E	1.7	1.50	3.0	4.01	0.33
Hip Add/Abd	2.7	2.80	2.4	2.29	0.77
Knee F/E	1.5	0.72	2.6	2.49	0.19
Knee Val/Var	1.1	1.36	1.7	2.82	0.53
Ankle PF/DF	1.1	0.40	1.1	0.50	0.86
Ankle I/E	2.4	0.85	2.8	1.21	0.41

GRF = Ground Reaction Force, AP = Anterior/Posterior, ML = Medial/Lateral,

V = Vertical, F/E = Flexion/Extension, Add/Abd = Adduction/Abduction,

Val/Var = Valgus/Varus, PF/DF = Plantarflexion/Dorsiflexion, I/E = Inversion/Eversion

p-value based on pairwise two-sample t-test; $\leq$.05

Table 14. Neurocognitive Function

ImPACT Domains	MHI Subjects		Healthy Subjects		p-value
	Mean	SD	Mean	SD	
Verbal Memory	84.10	9.94	88.30	9.17	0.34
Visual Memory	73.98	10.71	80.57	6.34	0.11
Visual Motor	36.72	6.05	36.89	1.94	0.94
Reaction Time	0.60	0.09	0.54	0.08	0.17

Mean, Standard Deviation (SD), and p-value from pairwise t-tests; $\leq$.05

Table 15. Relationship Between SEO Postural Stability and Neurocognitive Function

Variables	Verbal Memory		Visual Memory		Visual Motor		Reaction Time	
	r	**p**	**r**	**p**	**r**	**p**	**r**	**p**
AP GRF	-0.18	0.44	-0.05	0.84	-0.14	0.55	0.10	0.67
ML GRF	-0.17	0.47	-0.13	0.58	-0.23	0.33	0.21	0.38
V GRF	-0.18	0.45	-0.22	0.36	-0.03	0.90	-0.02	0.95
Total Sway	-0.10	0.67	-0.28	0.24	-0.10	0.68	0.06	0.82
Hip F/E	-0.07	0.77	0.14	0.55	0.16	0.50	-0.14	0.56
Hip Add/Abd	-0.05	0.83	0.12	0.60	0.12	0.62	-0.14	0.55
Knee F/E	-0.09	0.69	0.07	0.78	0.19	0.42	-0.15	0.53
Knee Val/Var	-0.07	0.78	0.13	0.60	0.17	0.48	-0.12	0.61
Ankle PF/DF	-0.11	0.64	-0.02	0.94	0.26	0.28	-0.20	0.39
Ankle I/E	-0.20	0.39	-0.01	0.98	0.13	0.60	-0.18	0.44

r = r-value and correlation coefficient, p = p-value; based on Pearson product moment correlation; ♋.05

Table 16. Relationship Between SEC Postural Stability and Neurocognitive Function

Variables	Verbal Memory		Visual Memory		Visual Motor		Reaction Time	
	r	**p**	**r**	**p**	**r**	**p**	**r**	**p**
AP GRF	-0.23	0.34	-0.09	0.69	-0.23	0.32	0.40	0.08
ML GRF	-0.07	0.75	-0.02	0.92	-0.14	0.57	0.25	0.28
V GRF	-0.15	0.52	-0.17	0.47	-0.02	0.94	0.08	0.73
Total Sway	-0.24	0.31	-0.33	0.15	-0.16	0.51	0.29	0.22
Hip F/E	-0.04	0.88	0.11	0.65	0.16	0.50	-0.10	0.69
Hip Add/Abd	-0.04	0.87	-0.08	0.73	0.08	0.73	0.01	0.99
Knee F/E	0.07	0.78	0.11	0.64	0.13	0.59	0.04	0.86
Knee Val/Var	-0.03	0.91	0.04	0.87	0.18	0.44	-0.12	0.61
Ankle PF/DF	-0.16	0.51	-0.36	0.12	-0.12	0.63	0.37	0.11
Ankle I/E	-0.12	0.61	-0.02	0.94	-0.10	0.68	-0.12	0.62

r = r-value and correlation coefficient, p = p-value; based on Pearson product moment correlation; ♋.05

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